

INVESTIGATION OF $^2H(d,n)^3He$ AND $^3H(d,n)^4He$ FUSION REACTIONS AS ALTERNATIVE NEUTRON SOURCES FOR BNCT.

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Abstract

Beam-shaping assemblies have been designed to moderate high energy neutrons from the fusion reactions $^2H(d,n)^3He$ (DD) and $^3H(d,n)^4He$ (DT) for use in Boron Neutron Capture Therapy. The low yield of DD is an obstacle for the treatment of Glioblastoma Multiforme. Our analysis shows that the high-energy neutrons from DT can be moderated to epithermal energy range without reducing the neutron flux to a negligible level. With the optimal beam-shaping assembly design for DT, a 1 A deuteron beam with energy of 120 keV leads to a treatment time of 50 minutes. The dose near the center of the brain obtained with this configuration is about 50% higher than the dose from a typical spectrum produced by the Brookhaven Medical Research Reactor (BMRR), and is comparable to the dose obtained by other accelerator-produced neutron beams.

1 INTRODUCTION

The main goal in this study is to identify some alternative accelerator-based reactions that could result in a simple and inexpensive accelerator and target system while satisfying all of the requirements for boron neutron capture therapy (BNCT).

The need for epithermal neutron beams with energy distribution peaking around 10 keV [1, 2] led different groups to investigate reactor- and accelerator-based neutron sources. Reactions such as $^7Li(p,n)$, $^9Be(p,n)$ and $^9Be(d,n)$ are currently being investigated as accelerator-based neutron sources for BNCT because the energy of neutrons is of the order of hundreds of keV [2, 3, 4]. The drawback of these reactions is the high energy of the protons and deuterons required, which varies usually between 2.3 and 4.0 MeV depending on the reaction, requiring a large accelerator and treatment facility.

To the best of authors knowledge, the reactions $^2H(d,n)^3He$ (DD) and $^3H(d,n)^4He$ (DT) have not been investigated so far for BNCT, because of the high energy of the neutrons produced, 2.43 and 14.1 MeV respectively. Provided these neutrons can be moderated to therapeutically useful regions without large losses, the high neutron yields for relatively low deuteron beam energy (100-200 keV) is a definite advantage over other accelerator-based neutron sources. A 120 keV deuteron beam yields approximately $3.7 \cdot 10^{11} n/sec/A$ and $10^{14} n/sec/A$ for DD and DT respectively [5]. This paper investigates the feasibility of generating neutrons for BNCT using the DD and DT reactions. It focuses on two points: designing a moderator to decrease neutron energies to epithermal regions and determining the dose distribution in a head phantom. Monte-Carlo codes are used for both tasks.

2 NEUTRON BEAM-SHAPING ASSEMBLY (BSA)

In order to obtain a therapeutically useful epithermal neutron beam, the BSA needs to be optimized. The neutron transport through the BSA is simulated using the Monte-Carlo code MCNP [6]. After moderation, a second Monte-Carlo code BNCT-RTPE [7] is used to calculate the dose distribution in a head phantom.

The neutron source is characterized as follows. Monoenergetic neutrons are emitted isotropically and uniformly from a 5 cm-diameter spotsize on a 40 cm-diameter target. Source neutrons enter a cylindrical BSA with a monoenergetic energy distribution. They travel through the cylinder composed of several layers of different materials until they reach the other side where the patient is located.

An accepted figure-of-merit used to measure the neutron beam quality is the dose equivalent to the tumor at the centerline of the brain, and it is based on biological criteria. The tumor dose at a

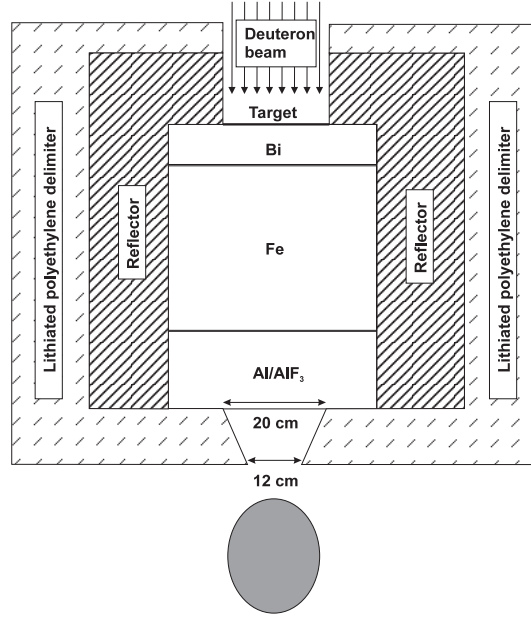


Figure 1: Beam-shaping assembly (BSA).

depth of 8 cm is used as a figure-of-merit in our study. This dose is limited by Brookhaven National Laboratory's (BNL) clinical trial protocol [8] which suggests that the local equivalent dose to the healthy tissues must not exceed 12.5 Gy. The treatment time will thus be limited by this value.

For the dose computation with BNCT_RTPE [7], concentrations of $13\mu\text{g/g}$ of ^{10}B in healthy tissues and $45.5\mu\text{g/g}$ of ^{10}B in tumor are used. The individual dose components (boron dose, gamma dose, nitro-dose and fast dose) are combined to yield estimates of total doses per neutron to healthy tissue and tumor, using the following equation:

$$D_{total} = CF * D_B + RBE_N * D_N + RBE_r * D_r + RBE_\gamma * D_\gamma$$

where the following assumptions are made: the normal tissue and tumor compound factors CF are 1.3 and 3.8, respectively; proton-recoil reactions RBE_r : 3.2; nitrogen capture reaction RBE_N : 3.2; RBE_γ : 1.0. The ^{10}B concentrations, compound factors and RBE factors were taken from values used in BNL's protocol [8].

2.1 Optimal BSA and dose distribution for DD

The optimal combination of materials that we came up with for DD was 30 cm of ^7LiF and 18 cm of 40%Al/60%AlF₃. The BSA is 25 cm in diameter and surrounded by a thin (0.5 mm) layer of ^6LiF and a thick 30 cm Al₂O₃ reflector. A detailed description of the geometry can be found in Ref. [9]. The

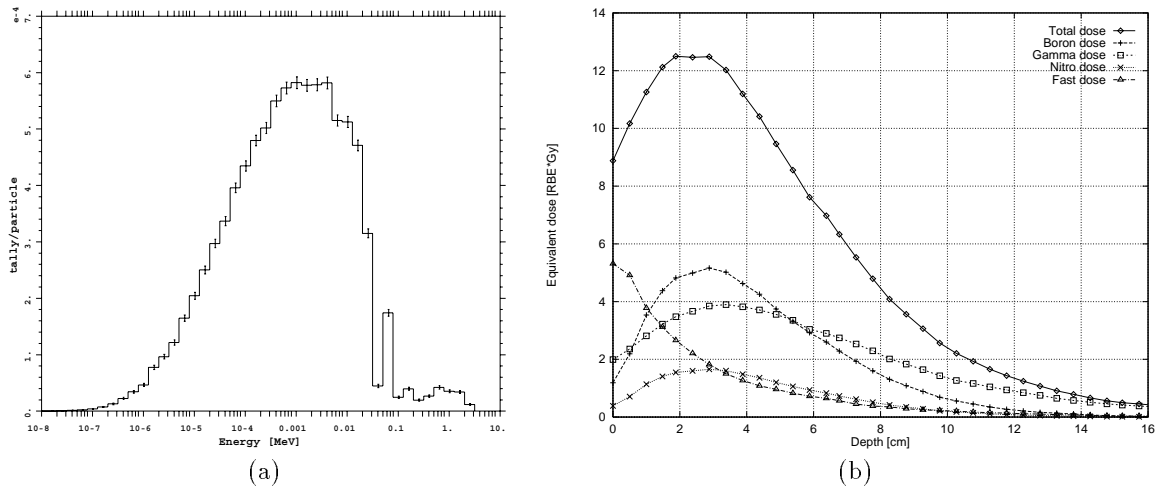


Figure 2: (a) Neutron energy distribution after moderation and (b) total dose to the healthy tissues with the different dose components in the head phantom.

neutron spectrum after moderation and the equivalent doses to the healthy tissues (with its components) are shown in Fig. 2. The equivalent tumor dose to the desired depth of 8 cm with this moderation is 18 Gy-Eq. The equivalent skin dose is 8.9 Gy-Eq. Accounting for the neutron yield of DD — which is $8.5 \times 10^9 n/sec/mA$ for a 400 keV beam [10] — this moderation would lead to a treatment time of 840 hours for a 5 mA deuteron beam. Even with a 1 A deuteron beam, the treatment time would be more than 4 hours. This unacceptably large treatment time could potentially be reduced by using several beams, by increasing the beam intensity, or by improving the beam shaping assembly.

2.2 Optimal BSA and dose distribution for DT

A few simulations for different combinations of materials showed that all neutrons above 1 MeV contribute not only to the fast dose at the surface of the brain, but also to the fast dose throughout the head, including the point of maximum tissue dose which limits the treatment time. The BSA optimization emphasis was thus on decreasing the high energy neutron flux to a level as low as possible.

The best BSA design we came up with was composed of thick layers of bismuth, iron, 40%Al/60%AlF₃, and of thin layers of ⁶LiF and lead. The BSA is surrounded by a 20 cm thick lead reflector. The large cross-sections of bismuth and lead for (n,2n) reactions are used beneficially to compensate for the neutron losses by leakage and absorption during the moderation. Iron is used to reduce the fast neutron energies from 14 MeV to around 1 MeV. The mixture 40%Al/60%AlF₃ is interesting in the sense that the elastic scattering resonances of aluminum supplement exactly the ones of fluorine from 27 keV up to the high energy tail, except for a narrow energy range around 70 keV. This resonance structure will preferentially reduce the number of neutrons above 27 keV. Lithium fluoride and lead are finally used to reduce the thermal neutron flux and to decrease the photon flux respectively at the end of the moderator.

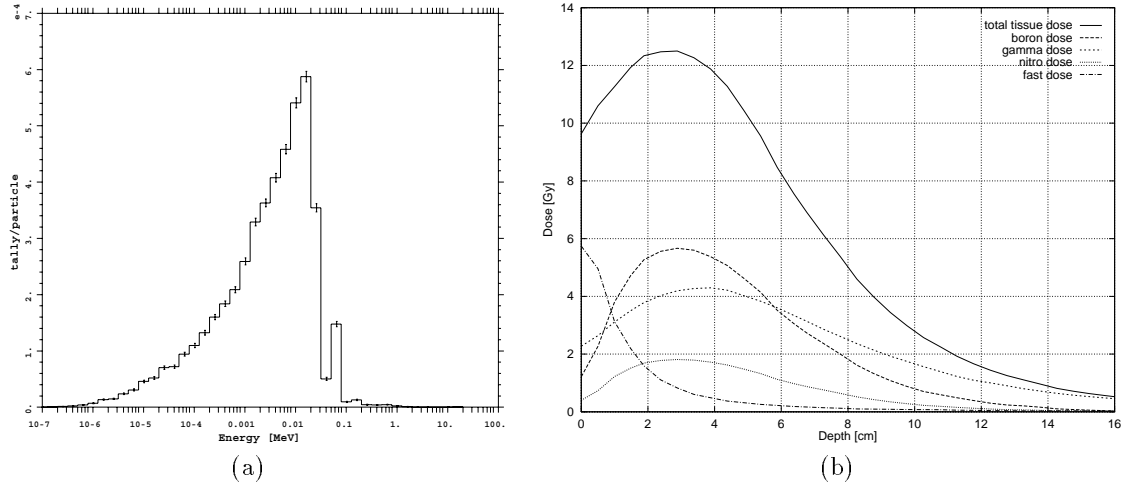


Figure 3: (a) Neutron energy distribution after moderation and (b) total dose to the healthy tissues with the different dose components in the head phantom.

The neutron spectrum after moderation and the components of the doses to the healthy tissues are shown in Fig. 3. With this moderation, the equivalent tumor dose in the head phantom at 8 cm depth is 21.9 Gy-Eq and the equivalent dose to the skin is 9.6 Gy-Eq. With a 120 keV deuteron beam, a 1 A deuteron beam intensity would lead to a treatment time of 50 minutes.

2.3 Summary and comparison with other neutron sources

Table 1 summarizes the main characteristics of the tumor dose distribution for DD, DT and other neutron sources proposed or used for BNCT. The optimized spectrum from the DT neutron source produces about 50% higher dose near the center of the brain than the currently used reactor spectrum at BMRR.

3 CONCLUSIONS

Two fusion reactions (DD and DT) have been studied as possible neutron sources for BNCT. The low neutron yield of the DD reaction is an obstacle for its use in this particular therapy. Neutrons from the

Neutron source	$^3\text{H}(d,n)^4\text{He}$	$^2\text{H}(d,n)^3\text{He}$	$^7\text{Li}(p,n)^7\text{Be}$	$^7\text{Li}(p,n)^7\text{Be}$	BMRR
Moderator	Bi/Fe Al/AlF_3	^7LiF Al/AlF_3	^7LiF [2]	Al/AlF_3 [2]	(Al_2O_3) [11]
Proton energy [MeV]	0.12	0.4	2.3	2.4	-
Proton current [mA]	1000	5000	20	20	(3 MW)
Treatment time [min]	50	50	40	54	39
Equ. tumor dose (max) [Gy-Eq]	64.8	60.1	64.3	65.1	61.6
Equ. tumor dose (5 cm) [Gy-Eq]	51.8	42.9	50.5	51.4	38.6
Equ. tumor dose (8 cm) [Gy-Eq]	21.9	18.0	21.4	22.3	14.5
Advantage depth [cm]	9.5	9.0	9.5	9.5	8.4

Table 1: Comparison of treatment characteristics for different neutron sources.

DT reaction could be moderated to around 10 keV without reducing the neutron flux to a negligible level. An equivalent tumor dose of 21.9 Gy-Eq could be achieved at a depth of 8 cm in the head phantom, which is about 50% higher than doses obtained by a neutron beam currently used at BMRR for clinical trials. For a treatment time of 50 minutes, the deuteron beam requirements are 120 keV and 1 A. Taking advantage of the small sizes of the ion sources and accelerators, several beams could easily be used in parallel and treatment times could be reduced to a fraction of an hour.

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